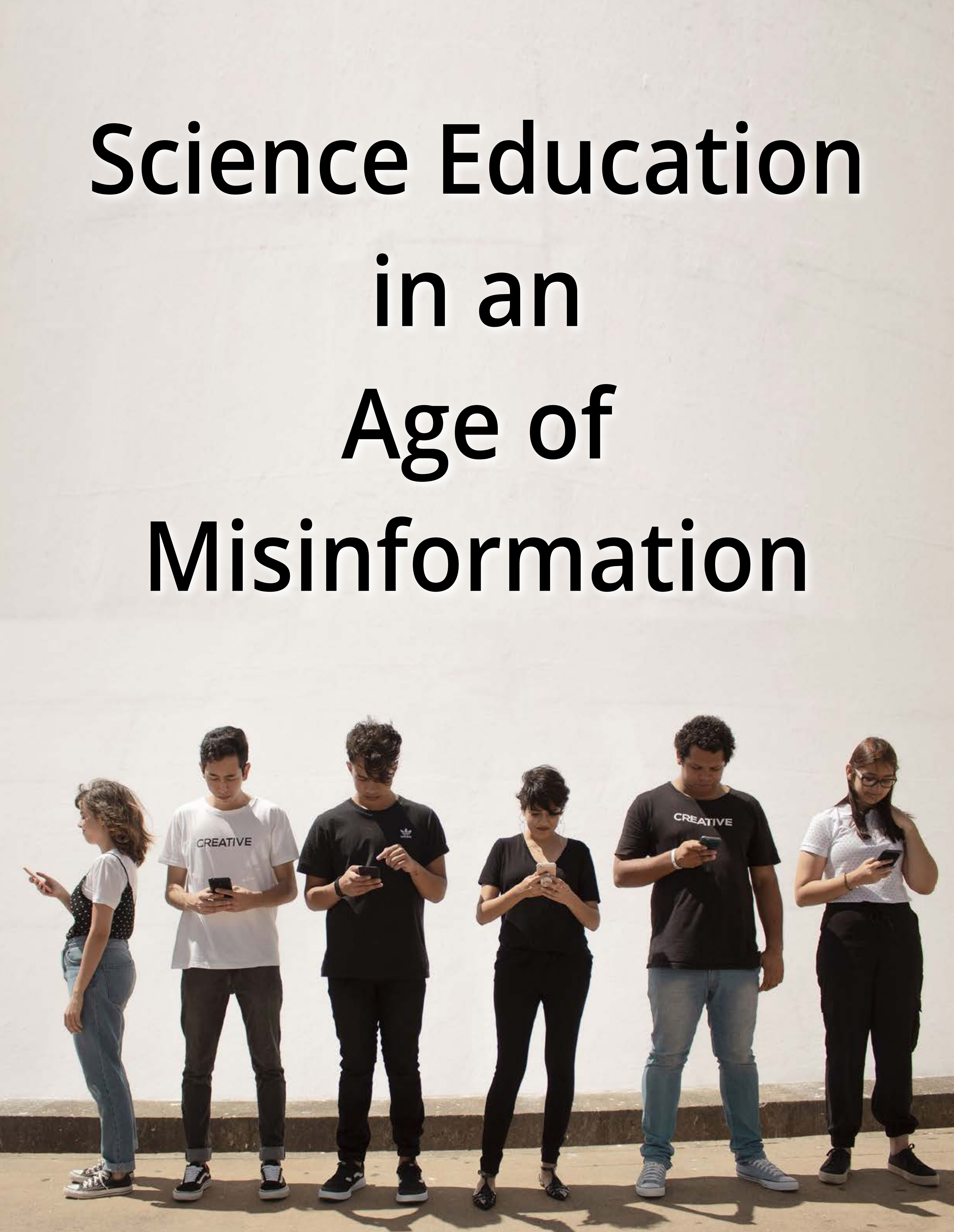
Science Education in an Age of Misinformation



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Jonathan Osborne, Stanford University, Stanford, USA

Daniel Pimentel, Stanford University, Stanford, USA

Bruce Alberts, University of California, San Francisco, USA

Douglas Allchin, University of Minnesota, Minnesota, USA

Sarit Barzilai, University of Haifa, Israel

Carl Bergstrom, University of Washington, Seattle, USA

Janet Coffey, Gordon and Betty Moore Foundation, Palo Alto, USA

Brian Donovan, BSCS Science Learning, Colorado, USA

Rena Dorph, The Lawrence, University of California Berkeley, Berkeley, USA

Kari Kivinen, Faktabaari, Finland

Anastasia Kozyreva, Max Planck Institute for Human Development, Berlin, Germany

Kathy Perkins, University of Colorado Boulder, USA

Saul Perlmutter, University of California Berkeley, Berkeley, USA

Sam Wineburg, Stanford University, Stanford, USA

Many of these participants are also authors of this document. And while there is broad agreement of all with the issues and concerns, not all authors concur with every point.

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THE CHALLENGE SCIENCE EDUCATION FACES

True knowledge is a collective good... Nevertheless, there is an increasing concern about the way the internet can be used to spread false information.

True knowledge is a collective good. Today the internet provides access to an interconnected sea of information that was simply unimaginable even 20 years ago. The common assumption is that this is a good thing as the internet offers us answers to questions about everything from how to fix a broken bicycle to our concerns about health issues. In addition, it has brought together isolated individuals to pursue their common interests.

Nevertheless, there is an increasing concern about the way the internet can be used to spread false information. Whether it is *mis*information (information offered in good faith but flawed) and, worse, *dis*information (information offered by those who are well aware that it is flawed or inaccurate)—much of it undermines trust in science [1–3]. The widespread acceptance of unfounded claims such as the idea that vaccines cause autism, that the Earth is flat, or that climate change is a hoax of grave concern. For, while true knowledge is a collective good, flawed or fake knowledge can be a danger—both individually and collectively. For instance, the idea that vaccines are harmful endangers not only the lives of those who hold this idea, but the whole community that depends on a high level of vaccination to ensure its health.

One characterization of this phenomenon is that we are living in a 'Post-Truth' society—one which diminishes or denies the role of facts in public life [4-7]. And while there have always been individuals who have advanced false information and conspiracy theories, or blurred the line between opinion and fact, the internet and social media provide platforms which disseminate lies at much greater speed, outstripping the communication of truth [3]. In addition, they offer the tools to disguise lack of expertise and to monetize its dissemination, thus shaping human behavior at a global scale [2,8].

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Much of this false information either attempts to undermine well-established science, or alternatively, to cloak ideas in the superficial trappings of science to make fallacious arguments. By using scientific jargon with links to journal articles and evidence, or by cherry-picking the evidence, the user is invited to evaluate the evidence for themselves, appealing to the notion that everyone can be intellectually independent. In short, do your own research. In this manner, purveyors of disinformation simply exploit a misplaced belief in our own capabilities to erode confidence in well-established scientific findings. The reality, however, is that we are all *dependent* on expertise [9-11]. Only experts within the same domain can evaluate the claims of other experts.

In addition, the information landscape has been fundamentally transformed. On the internet, information is often *not* curated by professional gatekeepers. Young people are likely to get their information from YouTube and Tik Tok. While some of the channels on these platforms are credible sources of information, many of them are not. In essence, we are living in a society where everyone is forced to make judgments about the credibility of information and our sources. Our inability to do this well, and the lack of education about how to approach the task, has unleashed a maelstrom that enables bad actors to exploit our limitations for their own ends. Scientists and science educators have watched with increasing dismay, frustration, and concern [4,11-14].

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Along with others, we see this development as a threat to the health of democratic societies, equivalent to the threat posed by the launch of Sputnik in 1957. That perceived threat led to major educational initiatives to improve the education of young people. This threat, too, needs a similar response. In particular, a major response from science education. Why? Because many of the issues requiring our personal or collective decision making are informed by an understanding of science. From deciding whether to take a vaccine to what actions we should take about climate change, science has an important contribution to make. However, sometimes the science may appear uncertain, contested or confusing. In these cases, it is difficult to know what decisions we should make. Knowing whom to trust, why they can be trusted, and how much they can be trusted is an essential life skill.

First, scientists and both formal and informal science educators must contribute to building the knowledge and capabilities required for *digital media and information literacy*, particularly in the sciences. Second, they must develop an understanding of the importance of *consensus in science*.

Living in an age of misinformation, two things must be done to address this challenge. First, scientists and both formal and informal science educators must contribute to building the knowledge and capabilities required for *digital media and information literacy*, particularly in the sciences. Second, they must develop an understanding of the importance of *consensus in science* and, in addition, *the social practices* the scientific community uses to vet knowledge claims to produce trustworthy knowledge. Currently, science education from elementary to undergraduate rarely, if ever, explains to its students how the sciences ensure that the knowledge they produce *can* be trusted. This omission does science a disservice and enables misinformation to spread, providing a space for the purveyors of disinformation to undermine the authority and legitimacy of reliable scientific knowledge.

In this report, therefore, we lay out how science education can meet its responsibility to provide all students with the competences needed to navigate this sea of false and questionable information without becoming lost, confused, and, more importantly, deceived. In so doing, we explore four questions:

1. **Why do students need the ability to evaluate scientific expertise and information?**
2. **What evidence is there that young people struggle to evaluate information effectively?**
3. **Why is it an urgent priority for scientists and science educators to develop students' competency to evaluate information?**
4. **What can be done by scientists and science educators to develop the competency to evaluate scientific information and expertise?**

We conclude with illustrative examples of what can be done now and with a set of policy recommendations for action.

1. WHY DO STUDENTS NEED TO DEVELOP THE ABILITY TO EVALUATE SCIENTIFIC EXPERTISE AND INFORMATION?

Thirty years ago, information sources were more regulated. Information was typically filtered by 'gatekeepers' in the news media. Their professional task was to edit and curate—essentially to filter the plethora of knowledge produced, evaluate what was significant, assess the credibility of sources, and report only trustworthy information. One consequence was that consumers might frequently encounter knowledge that challenged their way of thinking. For the sciences, this role was performed by science journalists and experienced science communicators. The issue today is not that they no longer exist (although their numbers are significantly diminished), but rather that the internet and social media enable them to be bypassed. Now the purveyor of flawed knowledge can present their claims to the public directly, often disguised as science, in a manner that seems credible to non-experts. The problem is then amplified by the fact that people can readily share such information on social media.

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Like it or not, as we are living in a complex society we are reliant on others' expertise [9,11,15]. The cars we drive, the airplane we fly, and the television we watch all require enormous expertise to function. Likewise, decisions about our health, how to deal with climate change, how to mitigate air pollution, and many others require the knowledge that experts have to offer, in this complex context, "*scientists are our designated experts for studying the world*." [16] Given this obvious truism, why then do so many seem to nurture an illusion that they are capable of cognitive independence [11]? A sentiment reflected succinctly in one British politician's statement in the UK Brexit debate "that people have had enough of experts." [17] Such beliefs threaten our trust in expertise and undermine our ability to deal effectively with the issues we face. Or, as some have suggested, to the four horsemen of the apocalypse—war, famine, pestilence, and death— we might add a fifth, disinformation.

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Clearly, there has always been more knowledge available than any one person can acquire in a lifetime. However, two things have happened that make this issue more pronounced. First, the body of knowledge has expanded from a pond, to a lake, to an ocean of information that continues to grow exponentially [18,19]. Second, since the development of the internet, public access to information is easier than it has ever been. Yet individual human capacities to process information have not adapted accordingly. Understanding and knowledge in the real world are limited both by our own finite cognitive capabilities and by the complexity of the environment—a principle that Herbert Simon called "bounded rationality." [20,21]

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The consequence for experts is that they are masters of a narrower and narrower furrow of understanding [22]. No longer does the undergraduate study a degree in biology but rather a degree in immunology or molecular genetics. Depth has been achieved at the expense of breadth. Expertise in one domain, however, is no guarantee of expertise in another. And, as our knowledge is always bounded [20,23]—the gap between the increasingly specialized disciplinary knowledge of the expert and the layperson grows daily.

Acknowledging the limits to what any one person can know is fundamental to shaping both the goals and outcomes of education. Given the finite limits to what education can achieve, all societies are forced to repeat the age-old question "What knowledge is of most worth?" [24]. The ideal envisioned by the great American educator and philosopher John Dewey—that it is possible to educate students to be fully intellectually independent—is simply a delusion. We are always dependent on the knowledge of others. Moreover, the idea that education can educate independent critical thinkers ignores the fact that to think critically in any domain you need some expertise in that domain [25,26]. How then, is education to prepare students for a context where they are faced with knowledge claims based on ideas, evidence, and arguments they do not understand?

The current approach in science education has a focus on developing 'marginal insiders,' that is, students who have "sat through a long parade of concepts and theories" and have a broad smattering of scientific knowledge [27]. While such knowledge is valuable, too often, the science that confronts us daily lies beyond the limited understanding achieved by formal education [27,28]. In contrast, given the bounded nature of our knowledge, unless we choose to become a professional scientist, most of us are destined to be outsiders, just as we are to all professions but our own. Education should, therefore, aim to make us 'competent outsiders' to professional science. In such a context, then, the question for the competent outsider is, can these claims to know be trusted? In short, is this information, and those who assert it, credible? Making that judgment requires an understanding of *science as a social practice*. That is how the scientific community vets and scrutinizes the knowledge claims that practicing scientists advance to ensure these claims are trustworthy. Take, for example, the IPCC report on climate change. Competent outsiders accept its veracity because they trust in the panel of experts who assembled this report and not because they evaluated the evidence for themselves. If you asked a competent outsider how they would justify their belief, they would refer to the track record of the sciences in providing reliable knowledge, the lack of discernible bias, the role of peer review, and the importance of consensus. Such criteria are what the competent outsider deploys judiciously to reach indirectly an informed view of whether the claims made about climate change are reliable and trustworthy.

> The key issue for the 'competent outsider' to professional science is, can these claims to know be trusted? In short, is this information, and those who assert it, credible? Making that judgment requires an understanding of *science as a social practice*.

In the absence of our own knowledge, it is rational to trust others based on their professional credibility among their peers. However, when making judgments about 'expertise,' a common tendency is to rely on the reputation of the source—that is, how their social status is perceived by us and by others [29]. In one sense, this is simply an efficient cognitive shortcut. Lacking the time, we tend to believe those whom we regard as leaders or those whom we regard as successful. Success in one field, however, is not an indicator of expertise in another.

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The problem with using social criteria as a means of judging whom to believe is that it can lead to informational cascades [29]. These occur when a group of people accepts an opinion without any evidence for its validity, and then disseminates it to others—something readily facilitated by social media. “Cascades develop because people ‘buy’ opinions...without checking what they are buying, because everyone else in their community has apparently made the same purchase.” In this situation, people trust in a form of ‘collective intelligence’ that selects for them the ‘acceptable’ opinions. Our reasoning being that, if everyone shares that opinion, there must be good reasons to believe it, even if we fail to investigate what those reasons are [29]. Judgments of reputation and trustworthiness may then arise simply from our perceptions of the source of the information and not whether they have relevant expertise. This tendency can be reinforced by the fear of acquiring a bad reputation ourselves for failing to adopt the group norm. For instance, those who live in communities where livelihoods depend on fossil fuels are likely to be immersed in a community that questions the existence of climate change.

In an age of misinformation, the initial questions when confronted with any claim to know must be: Is this source of information to be believed? What evidence is there for expertise and credibility? In short, is it trustworthy? Such a disposition must come from recognizing that there are limits to what we can know and that *we are dependent on expertise* [9,10]. Evaluating expertise, therefore, requires us to ask first, not is this true, but the very different question of is this source to be believed? And that requires a policy of circumspection—a stance which knows that “when the majority of experts are agreed, the opposite opinion cannot be held to be certain.” [15] Indeed, in the case of science, it is very likely to be false.

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The broad challenge is that the internet is a relatively novel information environment. Not knowing how to navigate the web and the reefs and rocks we may encounter can be dangerous. Young people need to understand the basic principles that would enable them to avoid the dangers they may encounter. Therefore, digital media education must be a basic requirement in all disciplines to enable students to take bearings and navigate this treacherous sea of information in an informed and competent manner. Or, to put it another way, if we are to be let loose at sea, it helps if we have a license to sail.

The narrower challenge, and the one that is specific to this report, is that much of this information has a scientific element. To evaluate that, what the competent outsider needs to understand is that for scientific information to be credible, it must go through a series of processes (discussed below) conducted by expert scientists with expertise in the relevant domain [16,30-32]. These processes allow scientific information to be vetted from multiple perspectives within the community to ensure that the information is reliable. While the process is not perfect, it eliminates most knowledge that cannot be trusted. Moreover, credible work builds on an edifice of knowledge that has been constructed over decades, if not centuries. Understanding how knowledge is established in science, and how consensual agreement emerges from its norms and institutional structures, *is vital* to establishing trust in science. And, if this knowledge and understanding is not developed by formal science education, where else will it be acquired?

In short, scientists and science educators have a new, critical responsibility to ensure that their students are equipped with the knowledge and strategies that can guard them against the snake oil salesmen and the agents of duplicity that inhabit the internet. Some of this knowledge is domain-general and some of it is specific to science. Developing this understanding would offer students a competency that is enduring and that can be used independent of a knowledge of the content of any specific science. In today's context, any education in science that fails to explain why and when science can be trusted does a disservice to the intellectual and moral achievement of the sciences and a disservice its future citizens [32-34]. Without this knowledge, individuals are simply adrift at sea.

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2. WHAT EVIDENCE IS THERE THAT YOUNG PEOPLE STRUGGLE TO EVALUATE INFORMATION SUCCESSFULLY?

A common assumption is that students are digital natives [35,36]. Immersed in digital technology, young people pick up the skills necessary to use today's technology in a fluid and informed manner. Evidence suggests otherwise. Young people and adults struggle with evaluating information [37,38]. A 2019 national survey of 3,446 high school students revealed major weaknesses in students' ability to evaluate the credibility of online sources [38]. For instance, 52 percent of students said that a Facebook video claiming to show ballot stuffing during the 2016 Democratic primary elections (a video that came from Russia—a fact easily established by searching for '2016 voter fraud video') constituted 'strong evidence' of US voter fraud. The authors state that, "nine of ten students were unable to come up with a cogent rationale for rejecting the video." [39]

A common assumption is that students are digital natives. Immersed in digital technology, young people pick up the skills necessary to use today's technology in a fluid and informed manner. Evidence suggests otherwise.

Students often say when interviewed that they would base their evaluations on the credibility of the information source. However, in practice, they usually ignore sources [37,40,41]. Instead, students often base their evaluations on surface-level features, such as the visual appearance of a website or the relevance of the information provided [42,43]. Moreover, students struggle to distinguish ads or sponsored content from news stories or other unbiased content. This is especially an issue in an online environment where there is monetary gain to be had from embedded ads and media providers use psychological profiles and personal information to target their displays and links [2,42].

As a 2019 survey revealed, students overwhelmingly judged websites on the basis of their top-level domain (i.e., whether a site was a dot-com or a dot-org), its appearance and design, links to other sites, and information on the About page [44]. Yet, the prevalent belief that a dot-org can be trusted as an independent source of information is incorrect [45]. For example, even very one-sided websites, such as answeringenesis.org or 911truth.org, use dot-org URLs. And, as Wineburg and Ziv point out, "while noteworthy nonprofits, civic organizations and religious groups have embraced the domain—so have a host of bad actors." Students from all demographic groups fared poorly, commonly making the faulty assumption that the higher up a site is in the search results, the more trustworthy it is [37]. Rarely did students leave the original website to consult other sources.

A democratic society depends upon access to true and reliable knowledge, and on the ability to distinguish knowledge that is flawed, incomplete, or that which aims to deceive from that which can be trusted. Hence, the chasm between the public perception of young people's competence and their actual performance [37,46,47] represents a growing threat to society, particularly when disinformation proliferates and young adults spend more and more time on digital devices.

In short, an overwhelming body of evidence suggests that while students are digital natives in their facility with the technology, they remain digital novices in their ability to evaluate the credibility and quality of the information they encounter. They may be in the digital sea, but they are rudderless, lacking the basic navigational tools that would ensure they are not deceived. And, without some basic fluency, how can they obtain reliable scientific information that would better inform *their* personal actions and *our* collective decision making?

In short, an overwhelming body of evidence suggests that students are not so much digital natives as digital novices. They may be in the digital sea, but they are rudderless, lacking the basic navigational tools that would ensure they are not deceived.

3. WHY IS IT AN URGENT PRIORITY FOR SCIENTISTS AND SCIENCE EDUCATORS TO DEVELOP STUDENTS' COMPETENCY TO EVALUATE INFORMATION?

At this point, the reader may be asking why should science education shoulder any responsibility for developing digital media and information literacy in the young? Surely this is the function of civic education? And anyway, at least in the USA, are not some of these issues addressed by the Next Generation Science Standards (NGSS)? While we understand this argument, our view is that the context has changed significantly since these standards were written a decade ago. The challenge posed to science by the age of misinformation is grave. Indeed, so grave that it demands an educational response from science educators.

Why? Because, fundamentally, many of the issues confronting us today have a scientific basis. In 2021, for instance, people have asked:

- Are face masks essential to controlling the spread of COVID?
- Is climate change responsible for floods, droughts, and other extreme events?
- Are vaccines effective?
- How dangerous is the Omicron variant of COVID-19?
- How do we prevent wildfires or mitigate flooding?

And then there are ongoing questions, such as: are GMO foods safe to eat; how can we best minimize pollution; and how can I lead a more environmentally friendly lifestyle? So, how is the non-expert, who does not know the science, to answer these questions? Questions where an understanding of how science produces reliable knowledge can clearly contribute to an informed and trustworthy answer. For unless scientists, science educators, and science communicators inform their audiences about why and whom to trust, others will fill the space.

The fact that science occupies the epistemic high ground is demonstrated by the fact that even anti-vaxers and climate deniers commonly cloak their misinformation in the language of science, using it to cast doubt on the scientific consensus [16,48]. For example, the fossil fuel industry advancing 'scientific' claims about climate change. Often, the sowing of doubt is all that is required to challenge the authority of scientific findings, even when there is a well-established consensus produced by a large, international, and diverse scientific community. Understanding the significance of consensus in science requires some knowledge of how it was produced by scientists and their social practices. Science educators, therefore, must explain why and when scientific claims in public discourse can or cannot be trusted.

What capabilities are needed? In short, the competent outsider needs to ask a

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series of well-defined questions and to understand their significance. Something which will only happen if students have been taught about their importance. Figure 1 offers a schematic overview of the approach we think needs to be taken to evaluating scientific claims on the internet.

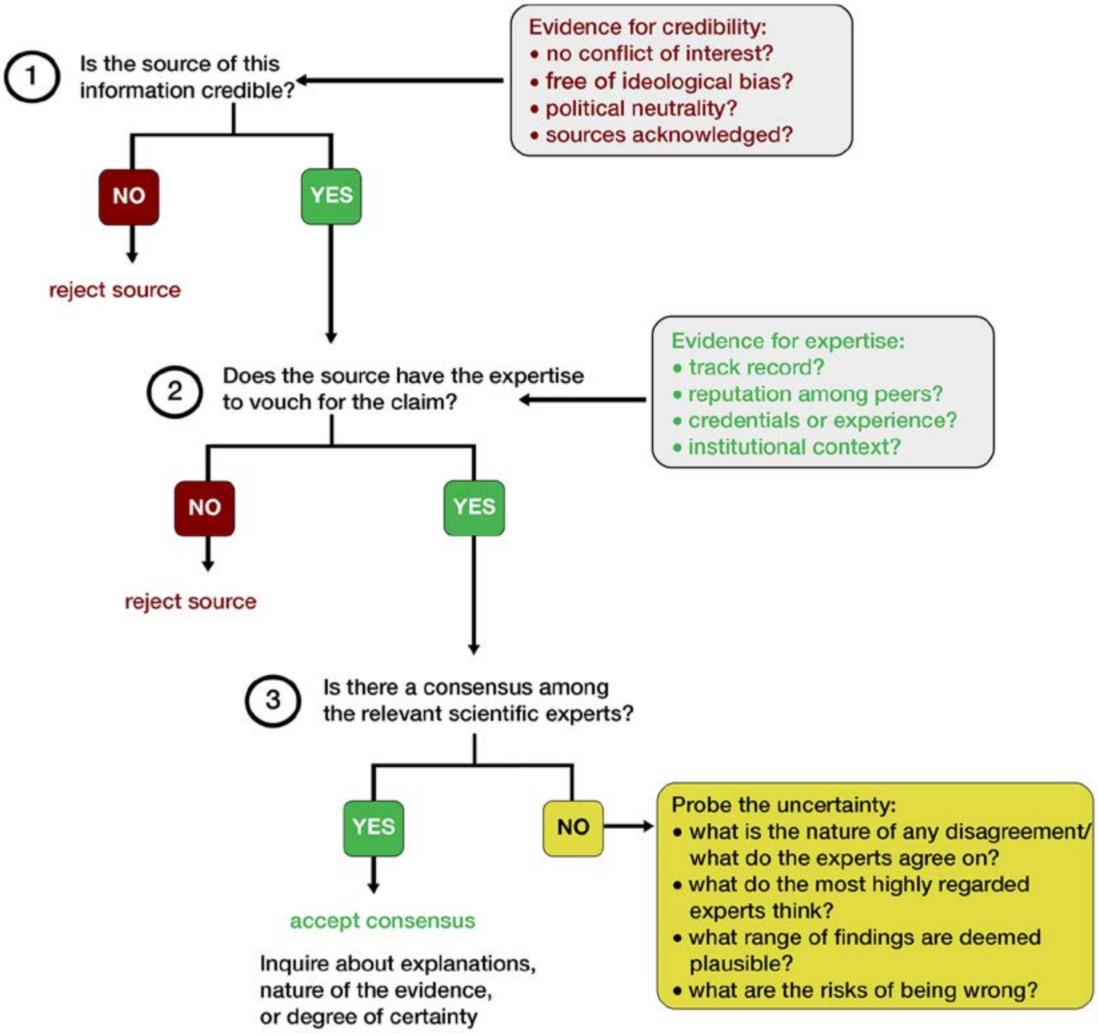

Figure 1: A decision tree for evaluating scientific information

Confronted with an unfamiliar scientific claim, the initial questions must be: Does this individual/organization have a conflict of interest? Is there evidence that they may be motivated by vested economic or political interests? If any answer is yes, much of the information has the same value as a paid advertisement and should be considered with a high degree of skepticism.

Only when initial research suggests that no conflict exists are the following questions worth pursuing:

- Does the individual/organization have relevant expertise?
- What is the standing of the author within the scientific community?
- Do they have a record of integrity?
- Does the author have the appropriate credentials or other relevant experience?
- Is there a strong scientific consensus among experts? If not, what do the majority of scientists think?
- How certain of the claims is the scientific community?
- Has the finding been vetted by similar experts and to what degree?

These questions are essential to an initial 'reading of the room.' Basically, what is the nature of the debate? How much, or how little, agreement is there? To obtain an answer in the English-speaking world Wikipedia is a good place to begin. The websites of major scientific institutions, such as National Academies of Science (www.nap.edu), and of long-established news media are also reliable sources of information.

The reader should note that the focus of these questions is on the *social practices the scientific community* uses to vet knowledge claims. An understanding of the answers is informed by a knowledge of the social nature of science—its norms, values, and practices. Yet none of this is commonly taught. It is only understood by insiders—the practicing scientists and engineers—and even then, often not fully [49,50]. If the goal is to develop citizens who are scientifically literate, then a core goal and aim of science education must be an understanding of how the social mechanisms function within a scientific community to enable the production of reliable knowledge [27,51,52]. Yet this social aspect of the sciences is notably absent from nearly all school science curricula and in the education of undergraduates. And if this knowledge is so vital to engaging with scientific claims and to validating the trustworthiness of experts, where else will it be taught other than in school and undergraduate science classes?

The focus of the questions worth pursuing is on *social practices the scientific community* uses to vet knowledge claims.

Essentially, students need to emerge from their formal science education with some understanding of the following: the traditional markers of expertise in science; the role of peer review; the significance of consensus among scientists; the standing of the journal, publication, or institution, be it governmental (e.g., the IPCC, the CDC, NOAA) or scientific (e.g., the National Academies, Royal Society etc.).

Moreover, competent outsiders need to know that science holds dear its commitment to evidence as the basis of belief, and that this commitment is fundamental to the trustworthiness of its claims to know [32,53,54]. And, while minor errors in science are common, the social structures of science are organized to expose and remedy these errors [55]. Yet we rarely teach to students the ways and means the scientific community has developed to protect against error. And again, if they are not taught in school or undergraduate education, how will this understanding be acquired?

Developing the capacity to evaluate evidence is fundamental for professional scientists. It is less so for competent outsiders, for the ability to interpret evidence is knowledge dependent [26,56], and competent outsiders commonly

Competent outsiders commonly lack the appropriate knowledge to evaluate conclusions from raw data, however well it might be explained.

lack the knowledge required to evaluate conclusions from raw data, however well it might be explained. Consequently, it is easy to be deceived by individuals whose argument is cloaked in the language of science. For instance, climate change skeptics argued that the expansion of sea ice in 2014 was irrefutable evidence that fears of that climate change were unfounded.[1] On the surface, the expansion of sea ice in a warming environment seems anomalous. However, a closer examination shows that the skeptics' case suffers from two flaws. First is the confusion between climate change (a long-term pattern observed over decades, if not centuries), and weather (a short-term variation in local atmospheric conditions). What matters is the long-term trend, which is not undermined by short-term exceptions.

Second, the water released by melting ice is fresh water, which is less dense than sea water and therefore floats on the surface. In addition, fresh water freezes at a higher temperature than sea water and produces more ice. The comprehensive answer is complex and still not fully understood by scientists. However, most outsiders could not be expected to identify the flaws in such claims.

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While science education has historically played a role in introducing students to domain-specific science ideas, it is simply not possible to introduce all the ideas that young people will need for the rest of their lives [4,28,57]. Moreover, most contemporary, science-related issues require scientific knowledge that is not taught in schools [28]. The COVID-19 pandemic, for instance, required an understanding of what viruses are, how they are transmitted, how they reproduce, how they affect the body, and why and how they change. Understanding the numbers of cases and deaths demands an understanding of exponential growth, logarithmic representations, and more. In short, school science cannot anticipate what kind of scientific knowledge will be required to deal with the next science-related, humanitarian crisis. In addition, the science of today (i.e., gene editing with techniques such as CRISPR) simply did not exist a decade ago. Likewise, three decades from now, what new scientific knowledge will there be which will not have been addressed in formal education?

In such a context, what knowledge would be of general and enduring value? As well as the major ideas of science that frame our understanding of the material world, we argue that it is the knowledge required to evaluate the credibility of a source. For example, the knowledge that enables you to determine whether to believe the above argument against climate change, or whether to decide if NASA is a credible scientific authority. Answering the key question of 'Can this scientific claim be trusted?' requires an understanding of the social structures of science. Hence, developing this understanding must be a *fundamental core component of all science education*, from cradle to grave—a feature of formal and informal science education and science communication.

Such a focus is missing because the current benchmarks for science education were developed for a very different context. We are now living in an age of misinformation and disinformation. To date, the common focus of science education has been the foundational concepts required to become a professional scientist. Such curricula give preeminence to disciplinary core ideas. In the USA, the NGSS devotes substantial time to "scientific practices" and the measurement of performance-based outcomes. Something we see as a notable improvement.

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[1] See earthdata.nasa.gov/learn/sensing-our-planet/unexpected-ice for a fuller description

Nevertheless, the focus is still internal to science and not on what the competent outsider needs to know. While the NGSS practice of "obtaining, evaluating and communicating information" might appear to address our concerns, it needs a much more detailed elaboration of the capabilities and knowledge required. For instance, the NGSS standards state that students should "gather, read and evaluate scientific information from multiple authoritative sources," but they do not specify the principles by which a student should judge a source to be "authoritative."

What matters in science is the production of reliable, trustworthy (although not infallible) knowledge to inform and guide our decision making and action [11,58]. Yet the commitment of science to producing reliable knowledge is never explicitly communicated in science education [59]. And if science and science education rarely explain why scientific knowledge can be trusted, how can it be valued by outsiders?

In short, the cultural context of media has changed dramatically in the past decade and what was fit for purpose yesterday is inadequate today. Today's society demands that students are given today's tools. What might these be?

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4. WHAT CAN BE DONE BY SCIENTISTS AND SCIENCE EDUCATORS TO DEVELOP THE COMPETENCY TO EVALUATE SCIENTIFIC INFORMATION AND EXPERTISE?

The Basics of Digital Media and Information Literacy

The picture painted so far may appear bleak. However, both school and university students *can* be taught strategies for evaluating common deceptive tactics and information online. A considerable body of work on what might be done in education has been carrried out by a group based at Stanford [39,42,44] and by the Suomi (natives of Finland) [60].[2]

Studies show that expert fact-checkers begin by taking their bearings. They refrain from asking 'should this information be believed?' Rather, they begin by asking the much more fundamental question of 'is this source credible?'

In developing our recommendations we draw, in particular, on recent studies in the USA [67] on how professional fact-checkers and journalists evaluate information on the web—an approach that has also been tested empirically with students [39,60]. These show that expert fact-checkers begin by taking their bearings. They refrain from asking 'should this information be believed?' Rather, they begin by asking the much more fundamental question of 'is this source credible?' The first task for the competent online reader is to locate where they are [68]. Why? Because like any skilled explorer, fact-checkers know that when one is lost, it is important to establish your position. Thus, the first question must be 'Who is behind this story?' In short, the initial focus must be on *questioning the source*, and not the content, its justification, or supporting evidence. Likewise, Bergstrom and West argue for three key questions: 1) Who is the source? 2) How do they know this? and 3) What are they trying to sell me? [69]

Taking bearings is essential when navigating an unfamiliar sea. Thus, expert fact-checkers typically leave the web page where they have landed within 30 seconds and open a new tab in their web browser. Then they search for information about the source—a strategy known as 'lateral reading.' They use sites such as Wikipedia, Sourcewatch.org, and Snopes.com to evaluate *not* the information presented *but the source itself*, by addressing the question of whether they are independent and trustworthy. In the case of scientific information, there are well-established scientific organizations whose credibility is dependent on providing reliable scientific information, such as the National Academies, the Royal Society, and the US Centers for Disease Control and Prevention (CDC).

The initial critical question is whether the source is independent, objective, and trustworthy, or whether it exhibits a conflict of interest or a particular ideological or political bias. Only when the credibility of the source has been established do expert fact-checkers return to the page itself. Untrained students, in contrast,

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[2] In addition, a considerable body of work has been undertaken with behavioral science interventions to tackle misinformation. These include (but are not limited to) "accuracy nudges" [61]; "inoculation" [6, 62–63]; "friction" [64]; "tips for digital literacy" [65]; and "debunking" [66].

usually stay on the page and attempt to evaluate it, or they meander to other sources on the same topic, which are often singularly unhelpful [42]. Lateral reading is, therefore, a basic tool, essential to determining credibility for the competent outsider.

Not only are seasoned fact-checkers suspicious of the source, but they also hold a critical orientation to search results. Notably, they scan the results page and decode the snippets of information on there before deciding which might be worth pursuing.

Another strategy is ‘click restraint.’ Not only are seasoned fact-checkers suspicious of the source but they also hold a critical orientation to search results. Notably, they scan the results page and decode the snippets of information there before deciding which might be worth pursuing. Commonly, they do not pursue the top results but pause to consider which seem most likely to provide the desired information before moving on.

Click restraint is invaluable for two reasons. First, the results of any search are very much dependent on the terms. Searching for ‘climate change true’ produces a very different set of results from searching for ‘climate change false.’ The information that appears first is often not the most salient and, moreover, is often paid for. Second, the order of results can be biased. Commonly, paid sources will appear first. More subtly, the search algorithm can be manipulated by a careful choice of terminology or by artificially inflated volume statistics. Hence, the top results are often not the most relevant or the most informative. Thus, not only does click restraint provide better information, it is also highly efficient in minimizing the amount of time that the user is lost at sea.

Notably, the approaches of professional fact-checkers differ significantly from many commonly advocated digital media and information literacy approaches that offer checklists for evaluating sources. As researchers have shown, such checklists—for instance, the one named CRAAP (currency, relevance, authority, accuracy, purpose)—do not help to expose deception or duplicity. Why? Because they do not ask primarily about the source’s credibility. Rather, they place too much emphasis on an individual’s ability to analyze the content or argument. They fail to recognize adequately the bounded nature of human rationality and the importance of first checking the credibility of the source. The outcome is that they leave most people none the wiser that the argument itself was flawed and that they were being deceived [70].

Fact-checkers’ strategies, in contrast, are akin to the routines that have enhanced performance across a broad spectrum of fields [71] (e.g., flying an airplane or conducting surgical procedures). These rank decisions in order of importance in a logically unfolding series, offering a potential exit at each point [72]. If we are to improve digital media and information literacy then acquiring the basic routines of professional fact-checkers must become an essential element of all formal education—from kindergarten to graduation. These simple tools will establish a routine for students of the first questions that must be asked to establish credibility. All students (and, for that matter, all adults) need such fact-checking routines to evaluate any new information that crosses their bow (see Figure 1 for an example).

Online readers will also benefit from a basic understanding of how the internet is structured, including how a SERP (search engine results page) is organized and how to decode Google’s conventions (such as the three vertical dots by a URL that show where and how deep the result comes from). And, that most websites are shaped by algorithmic decision making that influences what people see, based on data about the viewer [2,70].

Most importantly, all this knowledge of how to engage critically with digital information needs to be *explicitly taught* and acquired as an ingrained habit from grade 2 upwards. Just as you cannot learn to play the piano in an hour, neither can such competence be acquired in a one-off lesson. Digital media and information literacy must be taught and practiced until it becomes as natural as riding a bicycle. This is the approach that the Suomi have taken in developing a coherent curriculum for educating their youth from kindergarten to leaving high school [60]. Research has shown that even six hours of training in these fact-checking techniques can significantly improve performance [73]

Most importantly, all this knowledge of how to engage critically with digital information needs to be *explicitly taught* and acquired as an ingrained habit from grade 2 upwards. Just as you cannot learn to play the piano in an hour, neither can such competence be acquired in a one-off lesson.

The Social Practices of Science

Current curricula are ill-suited for the challenges we raise here. Even if 'Scientific Literacy for All' is adequately addressed by current curricula, none were written to address the challenges posed by this era of misinformation, conspiracy theories, and attacks on legitimate science. What knowledge, then, is required for this task?

The Indicators of Expertise in Science

If there is no apparent conflict of interest in a source or evidence of bias, the competent outsider then needs to establish whether the source has relevant expertise. Science is not some kind of democracy where, in the interests of balance, both sides of an argument are given equal voice. Rather, the competent outsider is forced to rely on experts. Those who lack the relevant expertise—regardless of their social stature or reputation—simply do not have the standing to speak on behalf of science. But what does constitute expertise—or the relevant expertise?

Research indicates that even individuals well-schooled in traditional forms of critical thinking are not proficient in assessing sources for their expertise [74,75]. In the case of any scientific claim, a crucial question is, 'is this individual a recognized expert in the field?' In choosing a lawyer, a plumber, or an architect, we look for the evidence of expertise: the certification, professional licenses, or the reputational recommendations that would lead us to trust the quality of their judgment. But how does one judge the expertise of a scientist? The answer is that the appropriate criteria resemble those for other experts, that is, judgments by other relevant experts, their past track record of work in the field, coupled with an awareness of potential biases and interests [11,76]. The questions that should be asked are:

1. What is their track record and, specifically, their publication record in the field?
2. Do they have standing within their field? For example, are they a fellow of a recognized scientific body, or have they won an award for their scientific work? Every professional group has watchdogs, boards, and certification authorities who police their own members to ensure that they live up to the standards of the profession and guarantee they are qualified to practice.

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3. What qualifications do they have? Is it a doctorate in the field? Or do they have other relevant experience, beyond formal credentials?
4. Where do they work? Is it for a recognized scientific body or research institution?
5. Is there any evidence of potential bias or pecuniary interest?

To become a practicing scientist requires years of training—generally, a minimum of an undergraduate degree and, for most, a PhD. Even a PhD only marks specialist knowledge of one very small field, which is not readily transferable. Expertise can also be acquired from professional training in science or from experience undertaking skilled work in certain contexts, such as: nurses and midwives working with patients; farmers' knowledge of the environment; or fishermen's understanding of sustainable practices. Those who lack any form of expertise do not deserve an equal voice in a debate.

Just being a practicing scientist, however, is not enough. The individual must be a practicing scientist *in the relevant field*. Being a Nobel prize winner in one field, does not make you an expert in other fields. Yet, individuals may easily lump all scientists together as undifferentiated 'authorities.' A specialist in radiology is not somebody you would ask for advice on viruses.[3] Being a scientist in *one* field of science does not make you an expert in *all* fields of science. A theoretical cosmologist knows no more about ecology than any other competent outsider. Yet, critics of science often enlist an expert in one field of science to challenge the scientific consensus in another field, typically using dubious or statistically manipulated evidence.

Just being a practicing scientist, however, is not enough. The individual must be a practicing scientist *in the relevant field* ... Yet, critics of science often enlist an expert in one field of science to challenge the scientific consensus in another.

For instance, a few physicists—famous veterans of atomic bomb research—were enlisted by the tobacco industry to question the association between smoking and cancer. Later, they served the oil industry by publicly doubting the link between burning fossil fuels and climate change. And finally, they made similar challenges to the role of fluorocarbons in ozone depletion and the role of burning sulfur-laden coal in producing acid rain. In all these cases, they had no expertise, no publications, and no program of research in the relevant fields. Nothing they claimed was supported by those who were experts in those fields. Yet to the naive non-expert, who commonly regards all scientists as one and the same, this deceptive media practice sowed seeds of doubt endowing legitimacy to such spurious claims. A similar strategy has been, and continues to be, extremely effective at hindering action to protect the environment and public health [48,77]. The competent outsider has to understand that all scientists are not the same. Relevant expertise matters.

While the criteria required to answer the five questions above may appear obvious to many a reader, they are not so to students who have received little to no education about the social norms and values that entitle individuals to claim the status of a qualified expert in science. In short, the appropriate measures of credibility (versus mere reputation) are not self-evident and must be taught explicitly—and taught explicitly in the context of science education as where else will it be done?

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[3] A good example of this occurred recently when Dr Scott Atlas, an expert in radiology, claimed the expertise to advise President Trump on how to deal with Covid-19 and advanced ideas that differed greatly from the scientific consensus.

How can the scientific community expect to be trusted when it does not ask its teachers to explain what justifies science's claims to authority?

How can the scientific community expect to be trusted when it does not ask its teachers to explain what justifies science's claims to authority? This is not to say that experts should not be questioned. Rather, that an understanding of who can legitimately claim to be an expert is a vital prerequisite to evaluating any scientific claim. Just using the language of science—or other cultural symbols of science such as white lab coats, graphs, and jargon—does not warrant the attribution of expertise, and is not sufficient to warrant belief.

How Science Produces Trustworthy Knowledge

The competent outsider needs an understanding of how a community of scientists, not just a single scientist or laboratory, reaches reliable conclusions. Such an understanding requires a knowledge of the social practices that are integral to the knowledge-building work of science.

The stereotype of a lone scientist in a lab, who dutifully follows the prescribed steps of 'the scientific method,' and arrives at a truth in an explosive, eureka-like moment, is highly misleading [78]. Moreover, there is no singular scientific method—often envisioned as a kind of quasi-algorithmic procedure for constructing new knowledge. The rationality of science is secured by a foundational commitment to empirical evidence and by inferences drawn from this evidence [54,78]. To achieve their goals, the sciences have developed a toolbox, which includes many styles of reasoning, combined with specific ways of protecting itself against enduring error [55,80,81].

The NGSS do ask students to engage in the scientific practices that require scientific reasoning and evidence, such as, designing experiments, arguing from evidence, and developing models. However, this is insufficient. There is "no scaffolding to get students from isolated individual practices" to an understanding of "the social and institutional practices of the various communities"—the practices that form the basis for our trust in science [82].

Contrary to the stereotypical image, it is a *suite of social practices* that is critical for transforming a tentative scientific claim into a generally accepted and unproblematic fact [83]. In short, reciprocal criticism, detecting error, and resolving disagreement through ongoing investigation, communication, and publication, together with other practices to construct an agreed consensus.

In addition, some awareness of the capabilities as well as the limits of science is needed. Uncertainty is intrinsic to the sciences and appears in many guises. Citizens and young people need some understanding of how uncertainty limits science's claims to know and how it deals with that uncertainty.

What the competent outsider might be expected to know about scientific consensus, the role of peer review, and the nature of uncertainty and its implications are three issues we turn to next.

Scientific Consensus

The goal of science is consensus—attained when the answer to an empirical question is so universally agreed that it is no longer of any great interest to investigate, and the field has moved on. Most school science textbooks deal in knowledge of this nature—knowledge that is unequivocal, unquestioned, and unquestionable [83,84]. Science-in-the-making, in contrast, is exactly the opposite as it deals in knowledge that is equivocal and questionable, advanced by experts who may legitimately disagree—sometimes in public. Resolution takes time, further investigation, and multiple studies before a consensus emerges. Without so much as a hint of the difference between well-established, consensually agreed science (the substance of formal science education), and contemporary, cutting-edge science (science-in-the-making), is it any surprise that formal science education leaves individuals puzzled and confused—or even angered—when science is unable to provide authoritative answers?

Without so much as a hint of the difference between well-established, consensually agreed science and contemporary, cutting-edge science, is it any surprise that formal science education leaves individuals puzzled and confused when science is unable to provide authoritative answers?

Citizens are often confronted by the need for information for decision making and action, where the science may be uncertain (e.g., whether a new virus variant is a larger threat than the previous variants). In such contexts, the essential first question is, 'is there a consensus or emergent consensus on this issue?' In the case of climate change, evolution, or the origin of the universe, the answer is an unequivocal 'yes.' In the case of threats posed by new virus variants or the long-term effects of novel medical treatments, the answer is less certain and more equivocal. Not surprisingly, individuals are confused. And, without any sense of the criteria needed to make a judgment, the challenge is eloquently captured by one individual's statement that, "I looked at the internet, there were 500 different opinions, I just didn't know whom to trust. I was scared and shut down." [85]

The importance of scientific consensus can be seen in the efforts to confound it in the public media. One method is to sow 'seeds of doubt' (as mentioned previously), another is to generate the impression that another consensus exists. In this vein, long lists of signatures against the fact of climate change—for example, the Leipzig Declaration and the Oregon Protocol—were assembled to convince the public that there was an 'alternate' consensus. Lists that were debunked as full of non-experts and persons with conflicts of interest. Ironically, such attempts acknowledge the epistemic authority attached to consensus in establishing claims inasmuch as naysayers are ready to promote and organize a false consensus. If the competent outsider is to be forearmed, they need to be forewarned and understand that it is only a consensus of relevant experts that matters.

If there is no consensus, the legitimate position is to doubt *anyone* who claims to know. However, if the evidence is unequivocal and the consensus among those with legitimate claims to expertise is overwhelming, any such questioning should be regarded with suspicion [15]. The scientific consensus is not some kind of groupthink—a mass delusion of experts. It has been established by extensive, careful, meticulous, empirical work that has been examined critically at all stages. While science-in-the-making is always open to question, one lone voice does not have the same weight as the overwhelming majority. All voices are not equal. Science teachers are thus fully justified in defending the settled science and accepted fact, despite any claims to the contrary in the media or online. Indeed, they should see it as an essential part of their role. After all, teachers of science speak for science and it is not acceptable for them to teach intelligent design or climate denialism [86].

The scientific consensus is not some kind of groupthink—a mass delusion of experts. It has been established by extensive, careful, meticulous, empirical work that has been examined critically at all stages.

Moreover, confronted with any questioning of the scientific consensus, the ensuing questions are not only 'Who speaks?' but also 'Who do they speak for?' Do they represent commercial, political, or ideological interests? Do they stand to gain from making certain claims about science and its consensus?

Our view is that science education has a fundamental responsibility to develop an understanding of the social mechanisms and practices of science for *resolving disagreement* and attaining its goal of consensus; failure to address this issue can no longer be justified. Such an omission not only fails science but also fails our future citizens. Thus, the very minimum required of any formal science education is some understanding of the significance of the role of consensus in science in establishing our trust.

Peer Review

Science is fundamentally a social and collaborative enterprise whose communal goal is the construction of justified, true beliefs about the material and living world. The process of peer review, in which new claims to know are vetted by peers who are also experts in the same domain of science, provides one important check among many against enduring error.

Viewed narrowly, the term ‘peer review’ refers to the process by which fellow experts evaluate written reports to determine their suitability for publication in academic journals, conference proceedings, or books. This basic understanding is reflected in the statement by Judge Jones in the *Kitzmiller v Dover School Board*, on the teaching of intelligent design:

> Peer review helps to ensure that research papers are scientifically accurate, meet the standards of scientific methods, and are relevant to other scientists in the field. Moreover, peer review involves scientists submitting a manuscript to a scientific journal in the field, journal editors soliciting critical reviews from other experts in the field and deciding whether the scientist has followed proper research procedures, employed up-to-date methods, considered and cited relevant literature and generally, whether the researcher has employed sound science [87].

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The review process takes time and reviewers typically evaluate manuscripts using a set of widely recognized criteria:

- Is the work methodologically sound?
- Are the conclusions justified by the data presented?
- Does the study constitute an original contribution to knowledge?
- Are the findings sufficiently significant to merit the time and attention of editors and readers?

However, this view of peer review is both too limited and too simplistic. The peer review process is not designed to catch every logical or methodological error in a scientific study, let alone to detect deliberate fraud. Peer reviewers do not attempt to replicate the experiments or even the statistical analyses described. Rather, the authors’ work is taken as having been conducted in good faith, by individuals of suitable skill to carry out the procedures correctly. As such, peer review cannot be a guarantor of correctness. By situating the work in the context of other research, it merely enriches the pool of published papers of work that is considered as competent and as a contribution to knowledge, however small.

Neither are the findings of all peer-reviewed publications of equal importance. Crick and Watson's paper on DNA, Mary-Claire King's on the genetic basis of breast cancer, or Jennifer Doudna and Emmanuelle Charpentier's on CRISPR, for instance, have much more significance than 99% of the papers that are published weekly, even in a journal such as *Science*.

While the process of pre-publication manuscript review is important, there is a much broader sense in which science relies on review by peers. Scientists begin vetting one another's work long before a manuscript is submitted to a journal and continue to do so long after publication. Most research funding is allocated through peer review of competitive grant proposals. Peers critique each other's work in the early stages of development: at scientific meetings; by sharing draft papers through informal communication networks; and in response to working papers or preprints posted to online such repositories as *arXiv*, *bioRxiv*, and *medRxiv*. Scientists also review and discuss each other's work after reports have been published, either in person, through correspondence, in meta-analyses of the research on a given topic, or on social and online platforms, such as pubPeer, that have been designed specifically for this purpose. Such vetting enables a more thorough evaluation through peer criticism at all stages of the process—which enables objectivity by exposing errors of execution and biases in interpretation [88].

Because peer review prior to publication is only a partial check on the validity of research findings, scientists rely on the communal and collaborative nature of scientific investigation to establish the trustworthiness of the findings; that is *peer review in the broader sense*. Moreover, one individual claim alone is rarely sufficient. Subsequent studies are needed, often using different methods, to confirm novel conclusions or to show how others can build productively on new findings. Independent replication by other scientists indicates that the same methods will consistently yield the same outcomes—another occasion to detect errors. The need for checking each other's work has led many to advocate for more open sharing of data and pre-posting of methods and standards of analysis. In short, science benefits from the organized critical examination by peers. In this manner, the community works to develop practices that help to expose biases and to remedy short-term errors. Only then is it possible to construct knowledge that can be trusted with growing certainty.

Because peer review prior to publication is only a partial check on the validity of research findings, scientists rely on the communal and collaborative nature of scientific investigation to establish the trustworthiness of the findings; that is *peer review in the broader sense*.

Building a consensus takes time. In 1989 Pons and Fleischman made headlines with remarkable claims about a "discovery" of cold fusion. Belief soared when other researchers reported successfully repeating their findings. However, within a few months a team of researchers with appropriate expertise demonstrated how critical flaws in the methods had led to misleading results. Peer review (in its broader sense) and subsequent research exposed the errors.

While the process can be complex, the basic idea of cross-checking, or of checks and balances, is easily understood—and this is what needs to be taught in science education. Science is *not* just about abstract logic, argument, and experiment, an essential element is also the social interaction that enables discourse and critique among many experts with multiple perspectives.

Thus, given the crucial role of peer review (in its broader senser) in establishing trust in science, it cannot be left to be acquired *en passant*—an understanding that may only be acquired by those who become practicing scientists. Rather,

Thus, given the crucial role of peer review (in its broader senser) in establishing trust in science, it cannot be left to be acquired *en passant* … teaching about it must become an essential element of any formal science education.

teaching about it must become an essential element of any formal science education. An informed public needs to have a deeper appreciation of how the social processes within science contribute to knowledge that can be trusted beyond the boundaries of the expert community.

Dealing with Uncertainty

What if there is no scientific consensus? What then?

School and undergraduate science occupies the landscape of settled science [89,90]. Yet, uncertainty permeates the development of scientific knowledge in almost all its stages: from identifying important gaps in our existing knowledge to imagining possible explanatory hypotheses; identifying relevant experimental variables and controls; conducting appropriate statistical analyses; and finally, how to communicate findings to the scientific community and the public.

Much policy-relevant science is science-in-the-making. Science-in-the-making occupies a different landscape of tentative but viable hypotheses, where findings may be disputed and where all claims to know are circumscribed with such modifiers as *may*, *possibly* or *likely*. Science's detractors capitalize on this difference and the failure of science to live up to the mythical ideal perpetrated by formal science education. For instance, in one widespread strategy, they set impossible expectations by "demanding unrealistic standards of certainty before acting on the science" [91]. Using misleading statements such as, "If scientists can't even predict the weather next week, how can they predict the climate in 100 years?" They incite doubt by implying that only science that operates with 100% certainty can be trusted. This impossible standard erodes the cultural authority of science—even when it is supported by an expert consensus [92].

Inasmuch as any knowledge of the material world can only be held with a degree of confidence, in an age of misinformation, a basic understanding of uncertainty is an intrinsic foundational requirement. Making predictions or judgments on the basis of such constrained knowledge necessarily involves risk. This does not imply that scientific knowledge cannot be trusted, but that uncertainty is something scientists have learned to live with by developing tools to limit the uncertainty inherent in empirical findings.

Acknowledging uncertainty marks an important shift in our approach to scientific knowledge, from a requirement of unequivocal certainty to one which is accurate enough [53]. Scientists recognize the varying degrees of confidence in their knowledge, which ranges from completely unknown (no conclusive evidence) to an expert consensus (based on accumulated evidence, multiple methods, vetting from numerous theoretical perspectives, and so on). Even then, some uncertainty may persist. Limited data can provide only so much precision. Technologies or methods may not be available to collect the observations that ideally could answer our questions. Alternative or unimagined explanations may be lurking unexpectedly around the corner. However, such limits do not threaten the importance of a consensus. The mutual agreement of relevant experts is the best criterion of trust available to us, even if that includes qualifications, caveats, or unknowns. Again, various purveyors of misinformation endeavor to discount scientific claims, based on a naive belief that, unless there is absolute certainty, such claims can only be doubted. In short, they disingenuously attempt, often successfully, to leverage the limits of science into an unjustified skepticism. Students need to understand enough about the nature of science and uncertainty to dismiss the idealized and unrealistic image of an unerring and absolutely certain science.

Schools still spend too little time teaching students the science of uncertainty and how it is addressed.

Thus, attempts to use the inherent uncertainty in science and empirical measurements to cast doubt are simply disingenuous. The correct question then, is not whether the science is correct, but “how confident can we be of these predictions?” Only then can we assess the degree of risk.

Schools still spend too little time teaching students the science of uncertainty and how it is addressed, that is: how to approach and understand scientific results expressed in numeric or probabilistic forms; the importance of the use of multiple studies; and how to make informed decisions based on limited information. In an ideal world, statistical thinking and risk literacy would become a required course of its own. In the real world, science education must step up to the plate.

One challenge for formal science education is that the data students commonly collect are often chosen because they exemplify simple linear relationships, such as Hooke’s Law, Ohm’s Law or simple cross-tabulations (e.g., Mendelian genetics). These phenomena can be relied on to yield predictable data sets with few, if any, anomalies. However, in real science data are messy and detecting signal from noise requires considerable methodological expertise.

Uncertainty can be seen in a simple plot of breath rate against pulse rate gathered before, during, and after exercise; in attempts to measure the length and width of a piece of paper or the boiling point of water and many other simple data sets.

And yet, there is no difficulty in exploring uncertainty. Uncertainty can be seen in a simple plot of breath rate against pulse rate gathered before, during, and after exercise [94], and in attempts to measure the length and width of a piece of paper or the boiling point of water, and in many other simple data sets. For instance, as Collins and Pinch point out, when asked to determine the boiling point of water—an activity of little value as everybody knows the answer (or, if not, can look it up in an instant)—“almost no one will get 100°C”. So, rather than attempting to convince students that they would have got the “perfect” result were “it not for a few local difficulties that do not affect the grown-up world of science and technology, with its fully trained personnel and perfected apparatus,” a much more honest approach would be to ask students how it might be possible to deal with the uncertainty that exists in their data [95,96].

Moreover, the internet now provides access to a range of data sets that exhibit uncertainty and, importantly, the tools to explore the relationships and patterns that might exist. Therefore, there is simply no excuse for uncertainty not to become a prominent feature of science education. What kinds of uncertainty, then, are readily addressed in science education that might help adults to live more comfortably with the uncertainty science produces?

Statistics and Probability Theory

Modern science relies on tools that allow it to deal mathematically with uncertainty—by applying rules of probability calculus. The rules of chance and the associated probability theory and statistics that emerged in the 18th century still remain the benchmarks of how to deal with risk and uncertainty for calculating the price of insurance; choosing between decision options; or testing scientific hypotheses (see Hacking, [97]) and more. Statistics and probability theory

A competent outsider needs to be able to interpret basic statistical information, and to identify common misleading tactics.

provide science with the basic tools and language to deal with uncertainty [98]. Moreover, making informed decisions in the modern world frequently involves statistical information (e.g., about risks of side effects or how to interpret positive test results [99]). The ongoing COVID-19 pandemic has made such knowledge salient for us all [100]. Yet the public lacks skills in interpreting information presented in this manner (e.g.,[101, 102]).[4] A competent outsider needs to be able to interpret basic statistical information, and to identify common misleading tactics (e.g., expressing changes in risk as percentage increases while ignoring the base rate). To help students deal with uncertainty in an informed way, the assessment and interpretation of statistics and risk must be taught, not only in science but also in mathematics [105,106].

Sampling

One pervasive form of error surrounding uncertainty is mistaking data from a small sample as a measurement of the whole population. Rarely are we able to measure exhaustively the entire population of objects that we study. Instead, we rely on sampling and statistical analysis. Hence, all results come with a margin of error and the larger the sample, the lower the margin of error. This is why, for example, large randomized clinical trials that minimize potential biases are considered a benchmark for scientifically reliable health policy. Undoubtedly, it is easy to cite individual cases as 'evidence,' particularly if they come from our own experience—indeed, one vivid story can seem very persuasive. However, just as one swallow doth not a summer make, isolated samples do not reflect the norm. They are not necessarily representative of all cases. However, using small or unrepresentative samples, with selection bias, is a frequent tactic that is the basis of misleading scientific claims in the media. The competent outsider should be especially wary of claims that use anecdotal data and small sample sizes.

Exploring these issues is not difficult. At the core of understanding sampling uncertainty is the concept of a normal distribution—something which is readily revealed by plotting a histogram of the heights of children in any one class. Predicting what the distribution of a sample in the adjoining classroom might look like can be done with a fair degree of confidence. Predicting what the maximum and minimum heights might be is much less certain. Samples in that sense are representative of a population and cannot predict individual measurements. Moreover, samples can be biased if the sample is not random nor representative of the whole population—for instance, by not using a separate sample of boys and girls when we measure heights or using only males to test the efficacy of a drug.

Causality

Science seeks to identify patterns in the world. Once a pattern is well-established the search for a causal explanation begins. Good examples are the correlation between latitude and the incidence of skin cancer [107]. Clearly, the causal explanation lies in exposure to sunlight, but why? Even then, just because there

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[4] A useful description of common pitfalls and practices involved in visualizing statistical information can be found in the work of David Spiegelhalter and colleagues [103,104].

is a correlation does not mean there is a causal explanation; establishing a relationship requires an understanding of the mechanism that links these two variables.

To investigate causal associations, students are commonly introduced to the control of variables strategy by investigating the effect of one factor on another (e.g., how temperature affects the amount of sugar that will dissolve in a fixed volume of water). While a good explanatory causal hypothesis (in this case, the particle model of matter) is a powerful explanatory tool, real life is complex and multivariate. In the absence of a causal explanation, science has developed sophisticated techniques to test associations. For instance, a randomized clinical trial is used to test the efficacy of drugs and other interventions. This approach excludes all factors other than the factor of interest—that is, whether the drug itself produces a notable difference in outcome. While it is possible that any positive effect occurred by chance, the scientific community has a means of assessing its likelihood and, if it is less than 1 in 20, commonly accepts this as evidence of a non-random effect. So, while the inherent uncertainty is acknowledged this criterion enables a considerable degree of confidence in the findings.

In the absence of a causal explanation, science has developed sophisticated techniques to test associations.

Students need an introduction to the notion of what a randomized clinical trial is, why it is necessary, how the evidence of an effect is measured, and what kinds of flaws it might suffer from. Given their import for the testing of drugs, the extension of these ideas to double-blind, randomized controlled trials also needs to be explained. Even then an association may be correlational rather than causal. Very few can readily detect abuses of this concept. Exercises are needed that require the mapping of causal connections, for instance: what is the possible causal explanation for the correlation between stork populations and number of babies born; what is the possible causal connection between the incidence of heart disease and latitude? The development of a good causal model that explains any phenomenon goes a long way to building our confidence and reducing our uncertainty about any pattern.

The Limits of Models

Science deals in complex phenomena. A goal of science is to answer the causal question of 'why it happens?' by constructing explanatory models [53,108]. And, in developing a model, "the aim ... is to come up with a representation that affords an understanding of the phenomena, not one that replicates the phenomena."[53]

Science, therefore, makes use of: representational models (e.g., the Bohr model of the atom); analogical models (e.g., explaining the behavior of an electric circuit by analogy with the behavior of the flow of water); mathematical models (e.g., the use of wave function in quantum mechanics). While models can never be complete, good models are true enough. True enough to provide a powerful explanatory representation of the world that can be used to make inferences or reliable predictions, even if there is a degree of uncertainty in their outcome. Climate models, models of the spread of a disease or of the variation in the demand for electricity, fall very much into that category. And the better the data on which the model is based, the more accurate and reliable are its predictions. Moreover, those models on which science bases decision making are commonly

While models can never be complete, good models are true enough. True enough to provide a powerful explanatory representation of the world and which can be used to make inferences or to make reliable predictions.

well-established and offer a high degree of confidence.

Part of that risk assessment is based on a knowledge of the limitations of the model. Models are selective in what they choose to represent. Moreover, many models have assumptions built into them—frictionless surfaces, point masses or idealized gases. In short, models are just that, models, and not a detailed representation of every feature. And thus, they cannot offer us certainty. They do not represent every feature in detail. Science educators, therefore, need to come clean with their audience and openly acknowledge that a model is just that—a model, a useful heuristic that helps us understand the material world and, in some cases, can enable prediction—although with limitations.

Misrepresenting Data

Increasingly, individuals are encountering data presented in a graph or chart. All such data visualizations must be read. Authors have choices in constructing such data which affect how they are perceived (e.g., whether to use a linear or logarithmic plot). Peddlers of disinformation often exploit people's inability to question and interrogate graphs and charts, using this weakness to deceive [69,109,110]. Axes or time periods are commonly cherry picked to exaggerate or minimize an effect. Thus, students need to be educated to read basic types of data visualization and to identify common flaws in their presentation and interpretation. In short, is the graphic supportive of the story it purports to tell?

Valuing Intellectual Humility and Truth

One unfortunate side effect of the almost instantaneous access to knowledge on the internet is that it deludes us into thinking that we can know more than we do [13]. At the press of a few keystrokes, we are provided with immediate answers to our curiosity. Yet knowledge is more than a collation of facts. In the case of science, it is not enough to know what an ion, an atom or a cell is. Rather, it is important to know how this entity or concept is related to others, what its significance is, how it came to be, and why this knowledge can be trusted. Knowing what photosynthesis is, for instance, is of little value by itself, but being able to explain its significance in the carbon cycle and climate change, however, is. In sum, how photosynthesis fits into the scheme of things that support life is an understanding that is acquired through extended study. Knowledge is not some miscellany of facts to be regurgitated at the press of a button or in response to an exam question; it requires a set of coherent, conceptual frameworks that integrate a set of complex interrelationships and explain the significance of each element. Such knowledge takes time to acquire. As Claude Bernard stated, "Science is a hall full of awe and wonder, the problem is the long dark kitchen you have to go through to get there."[111]

Confronted with a vast array of information, to which more volumes are added each day, the proper response should be one of intellectual humility born of an understanding of how little any one of us actually knows, let alone understands.

Confronted with a vast array of information, to which more volumes are added each day, the proper response should be one of intellectual humility born of an understanding of how little any one of us actually knows, let alone understands.

Intellectual humility is also required in the face of others who know more. In such a context, we need to acknowledge our own limitations, respect the expertise of others, and be ready to yield to convincing evidence or a better argument. Such an understanding of our limitations can only come by being exposed to errors—both our own and those of others.

Producing reliable knowledge is an enormous intellectual effort that requires painstaking systematic inquiry, which is the full-time professional occupation of dedicated scientists. The outcomes of their work is a remarkable track record of reliable knowledge of the material world—knowledge that is the foundation of our energy supply, transport systems, health care, modern agriculture, and much, much more [31,53]. Moreover, such knowledge enables humanity to act wisely. For instance, the opus of knowledge on climate change is forcing societies to consider how to meet the imminent challenges posed by human actions. In contrast, knowledge that is flawed or just plain wrong is a poor guide to action—something to which those who have denied the advice about COVID vaccinations and then been seriously ill, or even died, could attest.

Moreover, the sciences do not produce opinion. They are not an ideology.

Moreover, the sciences do not produce opinion. They are not an ideology. Only rarely do they involve inherent political commitments, although undoubtedly individual scientists do. Their priorities are a reflection of social, economic, and cultural values. Misinterpretations can happen, and have happened where science has been used for political ends. For instance, genetic concepts were once misused to support racist ideologies [112,113].

Part of the project of building intellectual humility requires exposing the common ways in which human reasoning goes awry. Some are generic. For example, all humans have a natural tendency to live in echo chambers—to socialize with those who think like them. In addition, as Kahneman has documented, the natural response is to think fast and to rely on intuition, when what is often required is a slower deliberative consideration of the issue, the evidence, and the trustworthiness of the source or sources [114].

Exploring an exhaustive list of error-types is beyond what science education can achieve. However, some are specific to science and mathematics [69,115,116] and should be explored, such as, mistaking correlation for causation, using outliers as the basis of an argument, making sweeping generalizations from small sample sizes (e.g., my granny is 90 and still smokes ten cigarettes a day) or ‘cheating’ with inappropriate scales on graphs. Thus, an appropriate curricular goal would be to introduce a broad sample of such errors as illustrations that exemplify a general problem and how they can be detected.

As well as humility being born of a recognition and experience of our own failings, it can be fostered by a sense of awe. Awe is an experience to be shared and fostered with all students [117,118] and sensed: when seeing the colors from white light produced by a prism in a dark room; in the tracks emerging from a radioactive source in a cloud chamber; or in producing a glass fiber and bending it 360o. Developing a sense of awe requires that “the anaesthetic of familiarity, the sense of ordinariness which dulls the senses and hides the wonders of existence” be shaken off [34].

Science has a story to tell which is *simply awesome.* For instance: all the substances that surround us are made from just 80 elements; you look like your parents because every cell in your body carries a chemically coded recipe about how to reproduce you.

Science has a story to tell which is *simply awesome.* For instance: all the substances that surround us are made from just 80 elements; you look like your parents because every cell in your body carries a chemically coded recipe about how to reproduce you; the planet we inhabit is just one of potentially millions in an ever-expanding universe which began 13.8 billion years ago. Developing a sense of awe requires teachers of science to recognize that they are tellers of a tale of the enormous intellectual and cultural achievement of the development of scientific knowledge. Their role is not just to pass on that cultural heritage but also to convey its value and the achievement it represents

The current emphasis on understanding the building blocks of science (e.g., the cell, Newton's law of motion, chemical v physical change) rarely provides students with a sense of wonder at the intellectual edifice science has constructed, such as our knowledge of the human body. It is as if so much science education asks its students to look through the wrong end of the telescope and then wonders why they seem so singularly uninterested.

To borrow an architectural metaphor, it is impossible to see the whole building if we focus too closely on the individual bricks. Without a change of focus, it is impossible to see whether you are looking at the Parthenon in Athens or a pile of stones, or to appreciate what it is that makes this building one of the world's great monuments. Students need to emerge from their compulsory science education able to explain why Dalton's ideas about atoms, Darwin's ideas about natural selection, or Rachel Carson's understanding of the effect of DDT on the environment, are among the most valuable and significant pieces of knowledge we possess. In short, if we do not communicate the value of what they learn, why should students value it themselves? And given the lack of emphasis on the achievements of science, is it surprising that, for many students, interest in science declines the longer it is studied; that science is not perceived as a creative subject; and that, if needed, the knowledge it offers could easily be retrieved with a quick Google search [119, 120]. Yet, offering students a vision of the hall of wonder and the 'big ideas' the sciences offer is fundamental to generating some sense of humility [121]. To do less is to do a disservice to the sciences and the work of scientists.

Part of the challenge to giving more emphasis to building a sense of humility and awe is the singular focus on reproducing the right answer. As Lapsley and Challoner ask, "how do we get students who have spent their entire academic careers chasing transcript values, that is, grades, awards, class points, and class rank—goods external to the practice of learning certainly—to desire knowledge and truth as a foundational pursuit for its own sake and out of a deep personal desire?" [122]. Clearly such a focus on testing and the recall of miscellaneous facts and concepts cannot communicate the deeper values of a respect for truth, or foster a deeper appreciation or sense of value of the science they have learned.

Imagine assessments that might promote not the ability to reproduce the canonical scientific knowledge but instead, the ability to spot the error, the flawed scientific reasoning, the inappropriate scale, or the weakness in the data on which a claim is based. Or assessments that demonstrate the ability to evaluate the credibility of dubious scientific claims. Such exercises would help to develop a 'truth-seeking stance'; one that recognizes that credibility matters, that only some sources can be trusted, and acknowledges that they may not know enough to render judgment.

> Imagine assessments that might promote not the ability to reproduce the canonical scientific knowledge but instead, the ability to spot the error, the flawed scientific reasoning, the inappropriate scale, or the weakness in the data on which a claim is based.

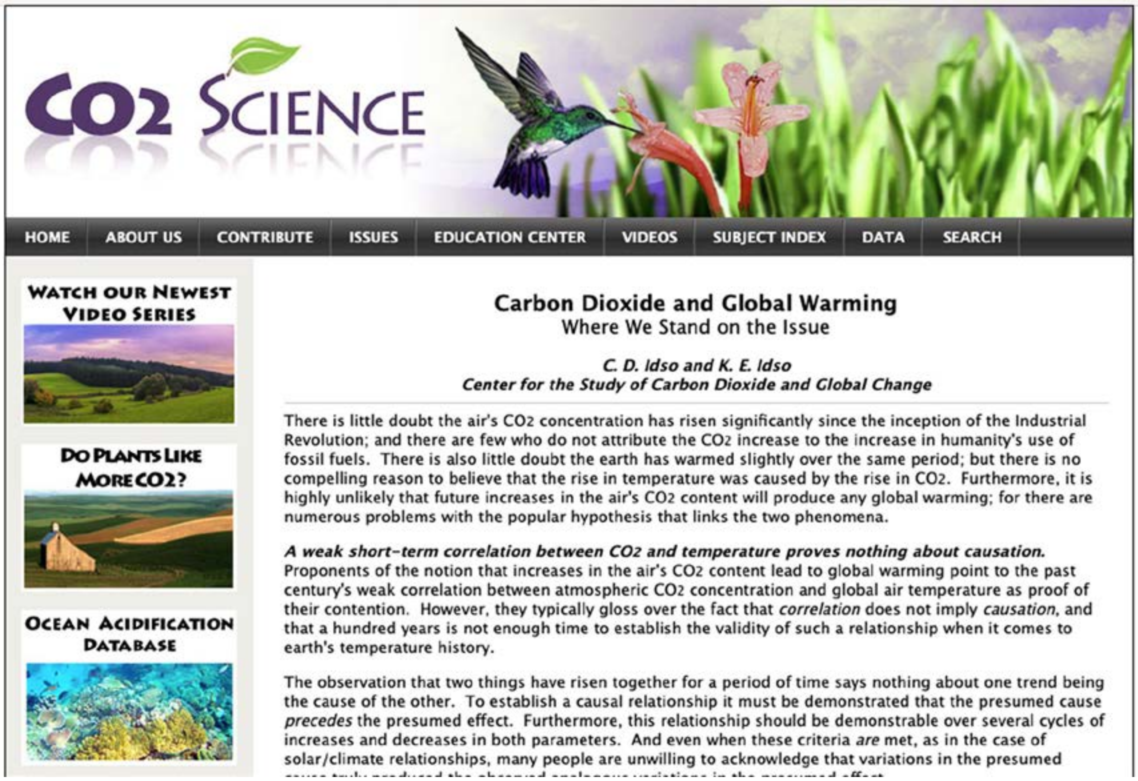
Teachers are rational actors and, as long as test scores are used as a measure of their performance, they will always be under pressure to teach to the test. Hence, new forms of assessment must reflect and value new educational goals and provide a context for guiding classroom learning goals, motivations, and rewards. Without such an emphasis, the increasing dissemination of misinformation is in danger of creating a citizenry who fail to recognize intellectual achievement and expertise. And, when ordinary citizens believe that no one knows more than anyone else, democratic institutions themselves are in danger of falling to populism or to technocracy or, in the worst case, a combination of both [11].

IMPLICATIONS FOR PRACTICE

We offer four examples for what attending to these new learning goals might mean in the classroom.

Example 1

In the context of teaching about climate change, students might be asked to evaluate the arguments found on the website CO2science.org. On the surface it is a dot-org which might predispose the individual to think it is unbiased.



Carbon Dioxide and Global Warming
Where We Stand on the Issue

C. D. Idso and K. E. Idso
Center for the Study of Carbon Dioxide and Global Change

There is little doubt the air's CO_2 concentration has risen significantly since the inception of the Industrial Revolution; and there are few who do not attribute the CO_2 increase to the increase in humanity's use of fossil fuels. There is also little doubt the earth has warmed slightly over the same period; but there is no compelling reason to believe that the rise in temperature was caused by the rise in CO_2. Furthermore, it is highly unlikely that future increases in the air's CO_2 content will produce any global warming; for there are numerous problems with the popular hypothesis that links the two phenomena.

A weak short-term correlation between CO_2 and temperature proves nothing about causation. Proponents of the notion that increases in the air's CO_2 content lead to global warming point to the past century's weak correlation between atmospheric CO_2 concentration and global air temperature as proof of their contention. However, they typically gloss over the fact that *correlation* does not imply *causation*, and that a hundred years is not enough time to establish the validity of such a relationship when it comes to earth's temperature history.

The observation that two things have risen together for a period of time says nothing about one trend being the cause of the other. To establish a causal relationship it must be demonstrated that the presumed cause *precedes* the presumed effect. Furthermore, this relationship should be demonstrable over several cycles of increases and decreases in both parameters. And even when these criteria *are* met, as in the case of solar/climate relationships, many people are unwilling to acknowledge that variations in the presumed

Figure 2 Article from Center for the Study of Carbon Dioxide and Global Change (/about/position/globalwarming.php)

This website claims there is a weak short-term correlation between science and temperature. It does not deny that CO2 concentrations are increasing but it argues that this is not the main cause of climate change and uses a range of arguments to critique the causal connection. The arguments appear scientific and are presented with evidence. For instance, they have a whole page of data called the Data Center. On the surface, such arguments might seem credible. For instance, they argue:

> that the warming predicted to result from a doubling of the air's CO2 content may be *totally countered* by: (1) a mere 1% increase in the reflectivity of the planet, *or* (2) a 10% increase in the amount of the world's low-level clouds, *or* (3) a 15 to 20% reduction in the mean droplet radius of earth's boundary-layer clouds, *or* (4) a 20 to 25% increase in cloud liquid water content. In addition, it has been demonstrated that the warming-induced production of high-level clouds over the equatorial oceans almost totally nullifies that region's powerful water vapor greenhouse effect, which supplies much of the temperature increase in the CO2-induced global warming scenario.
> (/about/position/globalwarming.php)

Superficially, it might appear that these arguments have substance. They are cloaked in the language of science; they appear to refer to published research and the work has been undertaken by an independent organization. Nothing could be further from the truth. To discover this requires that students engage in lateral reading, beginning by asking: is this source credible? By googling CO2science.org this website appears as the first search result, but underneath is the information that this is funded by ExxonMobil. Underneath that is the information that CO2science.org is funded by the Center for the Study of Carbon Dioxide and Global Change, which is identified by Wikipedia and Sourcewatch.org as a front group for the fossil fuel industry.

At this point a student should be encouraged not to attempt to evaluate the science presented on the website—they do not have the knowledge to do that. Rather, they should engage in lateral reading and ask 'what is the scientific consensus on climate change?' The top two sources come from NASA and Wikipedia: the first is a well-established scientific institution of considerable authority, which students may not know but which science education needs to teach them explicitly; the second has widespread credibility as an independent source. Going further, a third source is openscience.org, which offers a peer-reviewed article published in *Environmental Research Letters* with the title "Greater than 99% consensus in the Peer Reviewed Scientific Literature". Granted, at this point it would be unreasonable to expect teachers to know whether *Environmental Research Letters* is a journal of standing in the community. Nevertheless, the paper can be found along with many others [92]. Hence Bertrand Russell's maxim, "If experts are agreed, the opposite cannot be believed," should be applied [15].

Example 2

This example can be used when teaching about vaccinations. Students may be asked to evaluate the arguments presented on the website, childrenshealthdefense.org. Again, the website is a dot-org, which might make students believe the site to be unbiased. This URL creates an opportunity for classroom discussion about internet domains and the false idea that certain domains are indicators of quality and trustworthiness.

MARCH 28, 2022

It's Time to Follow the Science: COVID Vaccines

Figure 3 Front page on March 28, 2022 (childrenshealthdefense.org/child-health-topics/health-freedom/its-time-to-follow-the-science-covid-vaccines/)

In this case, the website claims that individuals should actively resist COVID-19 mandates, encouraging individuals to follow "the latest science tells us". The site includes a linked list of articles that are meant to serve as examples of lack of vaccine effectiveness in children. Many of the headlines refer to statistical information such as "at least 58% of kids already have natural immunity". The website draws on the authority of scientists with statements such as, "The science was never on their side."[5]

A website such as this one provides multiple opportunities for students to learn about the ideas we have presented throughout this report. As with the case of

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[5] As shown on March 31, 2022

CO2science, students should be encouraged not to start their evaluation of the website by attempting to decipher the claims it presents. Instead, students should be taught to engage in lateral reading to search for information about the scientific expertise of the people and organizations behind the website. A search for ‘Children’s Health Defense’ brings up the group’s webpage as the first result. Here, students should be taught to use click restraint by not clicking on the first result that appears. Instead, they should take time to read the search snippets, which contain information about the contents of each search result. For instance, the Wikipedia entry states that the Children’s Health Defense is “an American activist group mainly known for anti-vaccine activities and has been identified as one of the main sources of misinformation on vaccines.” (en.wikipedia.org/wiki/Children’s_Health_Defense) The result from National Public Radio (NPR) states that the organization is “an anti-vaccine group headed by Robert F. Kennedy Jr.” (www.npr.org/search)

1 Million Copies Sold — ‘The Real Anthony Fauci’ — The book that launched a movement. BUY TODAY!

04/04/22 • COVID › VIEWS

COVID Vaccines Don’t Prevent Transmission, Severe Illness or Deaths, Data Show

All we have to do is look at high-quality epidemiological data to get to the truth — COVID-19 vaccines aren’t preventing COVID or its transmission, and they aren’t preventing severe illness or death.

By Meryl Nass, M.D.

Let Thy Smartphone Be Thy Medicine? Google, Amazon Make Big Moves Into Healthcare

How Opioid Crisis Spurred Bill to Ensure Federal Contractors Are Working in Best Interest of American People

Exclusive: 34-Year-Old Died After Pfizer Shot, Mother Shares ‘Ridiculous’ Letters From CDC

How One Community

Figure 4 Article on April 4, 2022 (childrenshealthdefense.org/defender/covid-vaccines-dont-prevent-transmission-severe-illness-deaths-data/)

Another search, this time about Robert F. Kennedy Jr., reveals that he does not have any expertise relating to vaccines. He has a law degree and is a known anti-vaccine advocate. Kennedy’s lack of relevant expertise indicates that he is not a credible source regarding the science of vaccines, which casts doubt on the claims of his organization. This lack of credibility, along with broad scientific consensus regarding the safety of the COVID vaccines, can be used as justification to disregard the claims being made about vaccines by the Children’s Health Defense.

Example 3

In the context of a unit on nutrition, students might be asked to evaluate two websites that provide information on health. The first, Figure 5, is a page for Partnership for A Healthier America (PHA) (www.ahealthieramerica.org/); the second, Figure 6, is the page for the International Life Sciences Institute (ISLI) (ilsi.org)

An initial discussion, based on looking at each website, might show that students see both sites as credible. Both have an '.org' domain name and both websites appear professional and authoritative. Students can then be asked to use the decision tree shown in Figure 1 to determine which website they would choose to trust for health-related information.

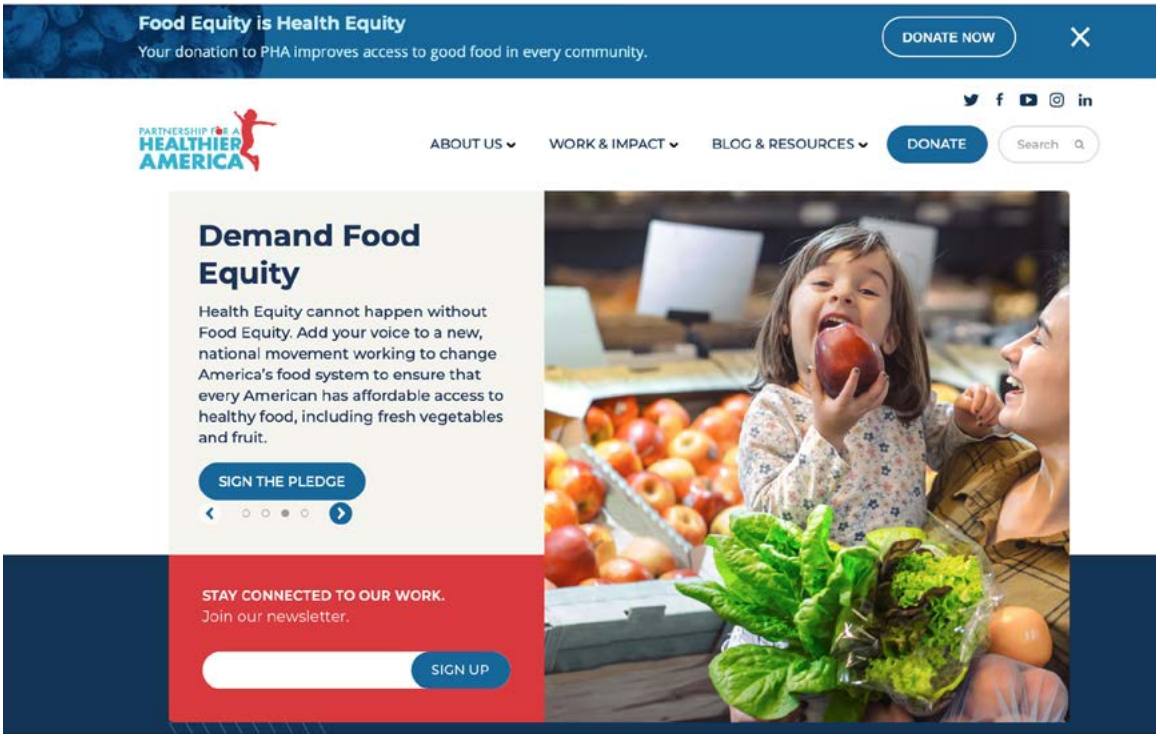
Beginning with the first question in the decision tree, "Is the source of this information credible?" students' first challenge is to determine whether these sources are free of bias and whether there are any conflicts of interest. To do this, they will need to open a new tab and begin with lateral reading.

If they search for 'Partnership for a Healthier America,' they will find that one of the first links to appear in the search results is from Wikipedia. After using click restraint to scan the snippets of information beneath each result and looking at the three dots beside each, they may decide to start with the Wikipedia page to get a broad sense of what other information is available about the organization. There students will read that PHA is a nonprofit organization focused on health and nutrition. Its president and CEO is Nancy Roman, who has years of experience working for world food programs, food banks, and nutrition non-profit organizations.

On the other hand, when students apply the same strategy to the ISLI web page, they are also likely to begin with the Wikipedia entry. This tells a very different story. While ISLI is also a nonprofit organization, the Wikipedia entry shows it was funded by a Coca-Cola executive and has numerous ties to food and chemical companies, such as McDonald's and Pepsi. Such ties represent a clear conflict of interest and would strongly suggest that ISLI is not a credible source of information.

A student who was not convinced could, nevertheless, proceed to the next question in the decision tree, asking "Does the source have the expertise to vouch for the claim?" Again, students will find further evidence for rejection. The Wikipedia page, for instance, gives examples of the organization's members publishing books that have been questioned as having "minimal scientific merit" and stating that authors, such as Michael Gough, are not experts on the topics they write about. Furthermore, the entry shows that other sources, with more credible scientific expertise, have concerns about the organization. *The British Medical Journal*, (a high-status scientific journal) claims that the organization has accepted funding from the tobacco industry.

Students can work in pairs with the decision tree, asking and answering questions. An ensuing class discussion can compare their findings and the judgments. Using examples such as this, the standard routines of fact-checkers can become internalized to develop the automatic routines required for checking the credibility of claims that abound on the Internet.



Food Equity is Health Equity

Your donation to PHA improves access to good food in every community.

Demand Food Equity

Health Equity cannot happen without Food Equity. Add your voice to a new, national movement working to change America's food system to ensure that every American has affordable access to healthy food, including fresh vegetables and fruit.

STAY CONNECTED TO OUR WORK.
Join our newsletter.

Figure 5 Point 3 on the front page slider of ahealthieramerica.org

Food Safety Snapshot

ILSI's food safety programs contribute to better prevention, detection, and response to intentional and unintentional contamination of our food and water systems.

Figure 6 Food Safety page under the Science and Research tab (ilsi.org/science-research/food-safety/)

Example 4

The fourth example is adapted from a set of activities developed by Allchin [123]. To teach students about the role of expertise in establishing credibility in science, teachers can provide students with descriptions of different individuals and task them with determining who to trust, using the criterion of *relevant scientific expertise*. For example, in a unit on climate change, students can be provided with the following three descriptions and, in small groups, be tasked with determining which of the following individuals best represents the perspective of the scientific community:

1. Fred Singer, physicist, head of the Non-Intergovernmental Panel on Climate Change, fellow at the Marshall Institute; founder of the National Weather Satellite Service; and former deputy assistant administrator for the Environmental Protection Agency;
2. John Coleman, co-founder of the Weather Channel, former TV weathercaster, with six decades of experience in broadcasting; or
3. Naomi Oreskes, historian of science with a background in geology and a former mining consultant, who undertook an analysis of the consensus about climate change published in *Science*.

Teachers can then engage students in discussion about which individual they chose as a scientific expert and their justifications to launch into a conversation about the characteristics of relevant scientific expertise.

In this case, Naomi Oreskes—ironically the historian—would be the individual most likely to represent and communicate the perspective of the scientific community on climate change. She has a scientific background relevant to the science of climate change (geology), and she has published an article on consensus in a well-established and credible scientific journal. While the other two individuals have also worked in leadership roles, neither has relevant expertise nor standing as a climate change expert within the scientific community. Although Fred Singer is a physicist, he is a member of the Non-Intergovernmental Panel on Climate Change, which has been criticized by the scientific community for producing reports with methodological flaws and using authors from irrelevant fields. John Coleman may have experience in journalism, but he is not trained as a scientist and has not conducted research on climate change. Thus, he should not be considered to represent the views of the scientific community.

During activities such as this one, teachers can engage students in conversations about important features of scientific expertise such as:

1. the role of relevant expertise, and that not just any science PhD or research position makes one an expert in all the sciences;
2. the role of consensus which should be weighed much more heavily than a single scientists' interpretation; and
3. the role of conflict of interest and biases which may lead even expert scientists to dishonest reporting.

Teachers can adapt the descriptions of the individuals that students evaluate based on the features of expertise they want to highlight, such as valuing expert knowledge over the prestige of titles, by including some non-experts who hold impressive leadership roles.

These examples are offered as illustrations of what might be done. Given the cornucopia of misinformation on the internet, we have little doubt that more and better could readily be developed.

IMPLICATIONS FOR POLICY

The challenges to science discussed in this document are grave and their remediation is urgent. While they cannot be solved by educators alone, education, and science educators in particular, have a contribution to make. We acknowledge that it will be challenging to ask science education to reduce its singular emphasis on knowledge and to develop the competency to better evaluate scientific claims in the media. Science education undoubtedly has a fundamental obligation to introduce its students to the major ideas of science—ideas which are beyond question. Given the finite time available much is already asked of the science curriculum. The emergence of the age of misinformation, however, has led to a fundamental change in context, and our goals and priorities must be reassessed. Do nothing, and we fail not only our students but science itself.

The challenges to science discussed in this document are grave and their remediation is urgent. While they cannot be solved by educators alone, education, and science educators in particular, have a contribution to make.

The previous four examples illustrate what teachers can do. Moreover, evidence of effectiveness exists [73]. At the undergraduate level, substantive work has already been undertaken by Nobel prize winner, Saul Perlmutter, together with his Berkeley colleagues, with their course on “Sense & Sensibility & Science” for undergraduates of all disciplines which, encouragingly, is being adopted at universities across the USA.[6] Likewise, a course by Carl Bergstrom and Jevin West called “Calling Bullshit: Data Reasoning in a Digital World” has resulted in an eponymous book which is being taught both in the US and internationally.[7] Few undergraduates, however, are likely to take such courses. Many more take an introductory college course in biology, environmental science, earth science, chemistry, or physics. These courses will often be the last science course that they experience. For this reason, all these courses need to address the issues we raise here.

However, it cannot be left to undergraduate education to remedy omissions in K-12 science. The challenges we have raised are real and ever-growing. All students need to develop the knowledge and understanding required to cope with the misinformation that is a fundamental threat to our societies. Inoculating students against the disease of misinformation must start in elementary education and treatment requires a sustained intervention. This is the approach that the Suomi (Finns) have taken [60]. We therefore make the following recommendations.

All students need to develop the knowledge and understanding required to cope with the misinformation that is a fundamental threat to our societies.

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[6] See sensesensibilityscience.berkeley.edu

[7] See www.callingbullshit.org

Recommendation 1: Revising Science Education Standards and Curricula

Given that the knowledge and competences we have discussed here are key to effective participation in a democratic society, they must be taught, and, if they must be taught, other elements must be excised. Given the extent of scientific knowledge and the finite time available for formal education, all curricula require choices. Our view is that there is little justification to ask all students to learn very specific elements of knowledge that they will rarely, if ever, use—the shapes of electron orbitals, the chemical structure of benzene, or the stages of meiosis and mitosis—when the knowledge we emphasize here is an essential requirement for the competency needed to address the flood of mis- and disinformation. Evidence would suggest that a small but sustained approach across K-12 would make a difference and leave considerable time to address the big ideas of science, scientific practices, and more. If the arguments we have made here are telling, then some of the 'sacred' content that populates most science curricula will have to be excised. Our view is that little will be lost and much will be gained, for both society and its students.

Clearly the next iteration of any curricula must make these choices. But to wait for that would be to wait too long. Both the scientific community and the science education community must acknowledge the urgency of addressing these issues in the classrooms they populate daily. We recognize that to many a scientist, science teacher, and parent these features of science will seem unfamiliar—simply not part of the grammar of their own science education. However, if the public is lost in a sea of misinformation, where trustworthy scientific findings are questioned for inappropriate reasons, both science and the public support for science will diminish. We cannot put it more bluntly than to say that the enemy is at the gates of Rome. Trust in western democracies is at its lowest ever [124]. Engaging with students and non-scientists to make the case for scientific expertise, why scientific consensus should be heeded, and explaining the intellectual achievements of science must permeate scientists' daily habitus. In short, scientists and science educators must explicitly espouse the value—and the values of—science.

In the case of schools, it means that teachers of science must go well beyond the lab activities which 'prove' again that Mendelian genetics, Newtonian mechanics, or the patterns of the periodic table are warranted. What the student needs to know is what justifies a belief in climate change, the efficacy of vaccines, or the drug that their mother takes to reduce blood pressure. Such knowledge is a product of a scientific community that enforces standards of honesty and trustworthiness which are second to none [32]. How this is achieved requires much more than the idealized and misleading description of the scientific method that populates the first chapter of so many textbooks. And, while the treatment of scientific practices in the NGSS goes some way to providing some insight as to what scientists do, students may still be none the wiser as to why scientific knowledge can be trusted. If this type of knowledge matters it should be taught and, if it should be taught, it must be an explicit feature of curricula.

Recommendation 2: Developing Curricular Materials

Clearly, both curricular materials and training are needed. Curricular materials are needed because few exist. The Stanford History Group, with its work on Civic Online Reasoning, has made a valuable start—some of which address scientific issues.[8] In Finland, the fact-checking organization, Faktabaari, has produced a body of materials to support teachers in developing competency for digital media and information literacy, as defined by the Finnish national curriculum.[9] UNESCO has produced a curriculum document for media and information literacy [125]. But these are predominantly domain general. Much more is needed in middle and high school science to develop digital media and information literacy in science and an understanding of science as a collection of social practices—specifically the role of consensus, peer review, and the features of scientific expertise. At the very least, curriculum developers need to add detail and clarity to the eighth practice in the NGSS of "Communicating, obtaining and evaluating information." Though innovative a decade ago, its focus must adapt to the new epoch of misinformation we face—by placing an emphasis on the needs of consumers of science and not just future professional scientists.

Just as Sputnik landed a symbolic blow to the American psyche, the age of misinformation threatens the very well-being of the scientific community and its work. Sputnik was the catalyst for a series of well-funded, curriculum initiatives, such as the Physical Science Study Committee (PSSC), the Biological Sciences Curriculum Study (BSCS) and Chemistry in Context (ChemCon) [126]. The threat of misinformation deserves the same response.

Recommendation 3: Training Teachers of Science

Training for teachers is needed because science teachers' own scientific education has rarely addressed these topics. Few will have learned about the role of argument and debate in science, peer vetting, scientific consensus, the evaluation of expertise, or digital media and information literacy. Historically, content has always been prioritized. To paraphrase Lakatos, scientists have thought that students had as much need to know about these features as fish do about hydrodynamics. Thus, rarely were they taught. Rather, the grammar of daily science teaching, and the zeitgeist which sustains its practice, continues to emphasize understanding its foundational content along with the scientific practices that are internal to science (e.g., planning investigations, developing models, etc.). Absent is any explanation of how the social and institutional structures of science ensure its goal of producing reliable knowledge. New content, new curricula, and new assessments, such as those advocated here, require courses in professional training—be they in person or online. Teaching these capabilities requires an understanding of why they matter and a knowledge of how they might be taught. Teachers cannot be asked to teach

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[8] See cor.stanford.edu/curriculum/collections/intro-lessons

[9] See www.faktabaari.fi/edu

about the social nature of science if they are not properly equipped and do not fully understand what they are being asked to teach. Subject knowledge matters and teachers who fully understand what they are teaching are better teachers [127,128]. Professional education and training are, therefore, essential. Such arguments are equally valid for those who teach undergraduates, informal educators, and science communicators.

Recommendation 4: Improving Assessment

No changes will occur, however, if these competences are not assessed. In the current educational context, what matters is what is counted. Notably, the OECD PISA assessment in 2025 will assess 15-year-old students' ability to "Research, evaluate, and use scientific information for decision making and action." This new focus is born of a recognition that we are living in an age of misinformation. However, much more is needed. Testing students' capability to identify flaws in scientific arguments—that is, explaining why the wrong answer is wrong—must matter as much as being able to justify why the right answer is right. Just as important is the ability to identify questionable sources of information, and to articulate why their trustworthiness should be questioned.

Our contemporary task, as noted in the introduction, is to sort reliable information from misinformation and disinformation. Testing students' ability to identify the flaws in common arguments or the deficiencies in the credibility of sources is central to the competency we are seeking to develop. This does not require a major shift so much as a gestalt shift in the way questions are framed and, we would argue, is readily implementable. Yet again, it requires an investment in developing new assessment items, evaluating their validity and reliability, and disseminating them widely through the relevant agencies.

In Conclusion

The internet has transformed the society in which we live. As well as its many benefits it has brought a flood of misinformation. Along with many others, we share the view that, left unchecked, the poison of misinformation is a fundamental threat to our societies. Trust in the institutions of our democracies is at its lowest ever. Resolving disagreement depends on a belief in objectivity and the ability to reason using trustworthy evidence.

What reliable scientific knowledge points to is invoked ever more strongly by teenage environmental activists such as Greta Thunberg, and by movements such as Extinction Rebellion in Europe—movements which are demanding that national leaders pay attention to what science has to say. It should not be left to the youth of today to make the case for why scientific evidence might matter. Scientists and science educators need to explain and justify how, when, and why science can be trusted.

We urge scientists, science educators, and policy makers to recognize and attend to these arguments, to prioritize them in their discussions and communications with each other and with outsiders. To develop the competency to obtain, evaluate, and communicate, information must be a focus of science classrooms, teacher training, teacher professional development, and the assessment of science. We cannot bemoan the plethora of misinformation if we are not prepared to defend what we hold dear. In short, to explain why science matters and why and when it should be trusted.

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